

Observed changes in maximum and minimum temperatures over China-Pakistan economic corridor during 1980–2016



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ABSTRACT

Pakistan is located in one of the fast temperature rising zones and hence, highly vulnerable to climate change. The dynamic variations of the maximum (Tmax) and minimum (Tmin) temperatures pose potential risks to the local people. Thus, the present study assessed spatiotemporal changes in Tmax and Tmin over China-Pakistan Economic Corridor (CPEC) during 1980–2016 based on the 48 meteorological stations across the CPEC. The non-parametric Mann-Kendall (MK), Sen's Slope (SS) estimator, Sequential Mann-Kendall (SQMK), and least square method tests were used to assess the long-term trends in Tmax and Tmin time series during 1980–2016. The results indicate that the trend of Tmax has significantly increased at the rates of 0.22, 0.37, 0.20, 0.23, and 0.31 °C per decade in winter, spring, summer, autumn, and annual time scales, respectively. Similarly, the Tmin exhibited a significant positive trend in winter, spring, summer, autumn, and annual time series with the rates of 0.33, 0.39, 0.25, 0.27, and 0.36 °C per decade, respectively. The spatial distributions of Tmax and Tmin represent a warming trend over the whole country; however, the seasonal and annual Tmax (Tmin) exhibited sharp increasing trends in the northern and southwestern mountainous (southern, southwestern and southeastern) regions of the country. According to the mutation test, most of the abrupt changes in seasonal and annual Tmax and Tmin trends have been detected during 1995–2010. The present study recommends that forthcoming studies should focus on the factors responsible for the spatial and temporal variability of Tmax and Tmin in the target region.

1. Introduction

Though the changes in mean temperature (Tmean) have been widely considered important indicators of climate change, but changes in maximum and minimum temperatures (hereafter Tmax and Tmin) provide more valuable information than the Tmean alone (Iqbal et al., 2016; Jhajharia and Singh, 2011; Safeeq et al., 2013). According to the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5), the trend in Tmean may be due to changes in either Tmax or Tmin, or relative changes in both (IPCC, 2013). Donat et al. (2014) stated that the global Tmax and Tmin showed a warming trend since 1950. However, the trends in Tmax and Tmin are not uniform, but vary

over space and time (Barry et al., 2018; Lelieveld et al., 2016; van Wijngaarden, 2015; Yao and Chen, 2015). Recent studies have reported that the increase in warming trend is mostly associated with considerable increases in Tmin than in Tmax (Abbas et al., 2018a; Khan et al., 2018; Sun et al., 2017; You et al., 2017). The spatial and temporal variations of Tmax and Tmin can be the result of land cover changes, deforestation, agricultural practices or/and other anthropogenic activities (Balling et al., 2016; Changadeya and Kambewa, 2012; Roy et al., 2016). The dynamic changes in Tmean due to Tmax and Tmin ultimately lead to surface warming and climate change (Abbas, 2013; Del Rio et al., 2013; Shahid et al., 2012). Thus, due to their prominent role in global climate change, the assessment of long-term changes in Tmax

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and Tmin has gained significant attention in recent years (Jhajharia and Singh, 2011; Revadekar et al., 2013; Sayemuzzaman et al., 2015). Furthermore, the analysis of long-term variability and the tendency of Tmax and Tmin is critical for detection and quantification of the potential impacts of climate change on the human environment (Ren and Zhou, 2014; Ren et al., 2017; Sun et al., 2017).

The variability of Tmax and Tmin has more effects on the natural and built environment than Tmean (Del Río et al., 2013; Khan et al., 2018). It has also been reported that the spatiotemporal changes of Tmax and Tmin have significantly affected the intensity, frequency, duration, and spatial extent of temperature extremes around the world (Donat et al., 2014; Li et al., 2012; Rahimi and Hejabi, 2017; Salman et al., 2017; Sun et al., 2015). Moreover, the observed changes in Tmax and Tmin have great implications for food productions, natural ecosystems, loss of biodiversity, freshwater supply, and increase health risks (Qasim et al., 2016). On the other hand, Iqbal et al. (2016), indicated that the variability of Tmax and Tmin has a vital role in agriculture, especially, in the development and growth of plants. However, the intensity of Tmax and Tmin beyond the threshold level can adversely affect the agricultural productivity (Abbas, 2013; Rao et al., 2014). Furthermore, the variations in Tmax and Tmin have a direct impact on the crop water requirement, which influences evapotranspiration and soil moisture content (Jhajharia et al., 2012; Zhang et al., 2013). The spatiotemporal variability of seasonal Tmax and Tmin coupling with precipitation can also affect the availability of water for drinking, irrigation and other domestic purposes (Gardelle et al., 2012; Kääb et al., 2012). Thus, the analysis of long-term changes in Tmax and Tmin is critical for understating the impacts of climate change, especially, in agriculture-dependent country like Pakistan. A developing country like Pakistan needs improved knowledge and profound understanding regarding temperature fluctuations and their influence on agriculture, food security, water resources, and temperature extremes (Iqbal et al., 2016; Khan et al., 2018; Rao et al., 2014; Zhang et al., 2015). Moreover, this information can play a vital role in long-term planning for climate change adaptation at the regional and local levels (Ali et al., 2016; Berardy and Chester, 2017; Ragettli et al., 2016).

Pakistan is located in one of the fast temperature rising zones and hence, highly vulnerable to climate change. Several studies have reported dynamic fluctuations in Tmax and Tmin over different parts of Pakistan (Iqbal et al., 2016; Khan et al., 2018; Rahman and Dawood, 2017; Sajjad et al., 2009; Samo, 2017; Sun et al., 2017; Zahid et al., 2017). A recent study showed that the annual Tmax and Tmin are sharply increased over the whole country at the rates of 0.17–0.29 and 0.17–0.37 °C per decade, respectively (Khan et al., 2018). Iqbal et al. (2016) also found a positive trend in Tmax and Tmin at seasonal and annual time scales in most parts of Pakistan. Similarly, increasing trends were detected in Tmax and Tmin over the entire country at the rates of 0.12 and 0.10 °C per decade, respectively (Qasim et al., 2016). By analyzing monthly data for the period of 1967–2005, the trend of Tmax (Tmin) has been increased with 0.84 (−0.62), 0.40 (−0.96), 0.54 (−1.35) °C per 39 years over the upper, middle and lower basins of the Indus River, respectively (Khattak et al., 2011). Similarly, Rahman and Dawood (2017), also reported an increasing (decreasing) trend in Tmax and Tmin over northern Pakistan. However, Ahmad et al. (2014) found a positive trend in Tmax (Tmin) in the middle and lower Indus River basin with 0.16 (0.29), 0.03 (0.12), 0.01 (0.36) and 0.04 (0.36) °C per decade during spring, summer, autumn, and winter seasons, respectively. Though, the above-cited studies have reported significant results in terms of dynamic variability of Tmax and Tmin over Pakistan. However, those studies were either limited to a specific region, low stations' density, less temporal coverage, different data sources or/and methodologies (Ullah et al., 2018). Thus, the present study is an improvement in terms of the study of the China-Pakistan Economic Corridor (CPEC) region with the extended time scale, stations' density, and additional statistical analysis. Furthermore, no comprehensive study has been made so far, to assess the spatial and

temporal changes in Tmax and Tmin over the CPEC region. Hence, the current study aims to determine the observed changes in Tmax and Tmin over CPEC (Pakistan) during the period of 1980–2016.

The CPEC is one of the mega projects of the One Belt and One Road (OBOR) initiative (Ahmar, 2016). The project is initiated by the Chinese government with the aims to ensure regional peace, integration, co-operation, and economic growth (Esteban, 2016). However, climate change and its related risks could become the potential threats to achieve these targets. Several studies have indicated that the CPEC region is highly prone to climate change and hydro-meteorological disasters due to dynamic variations in temperature (Qasim et al., 2016; Rahman et al., 2018; Yamada et al., 2016; You et al., 2017). In recent decades, the region has been affected by several climate-induced disasters, which resulted in extensive damages to human lives, property, and the environment (Mueller et al., 2014; Rahman and Khan, 2011; Zahid and Rasul, 2012). Therefore, it is essential to assess the spatial and temporal changes in Tmax and Tmin and propose effective recommendations for climate change adaptation and disaster risk reduction in the region. The current study has thus focused on observed changes in Tmax and Tmin over the CPEC region for the period of 1980–2016. This study is the first of its kind to detect abrupt changes (mutations) in seasonal and annual time series of Tmax and Tmin in the target region.

2. Study area

The CPEC is one of the pilot projects of the Belt and Road Initiative (BRI) with an estimated cost of 62 billion US dollars (Irshad et al., 2015). The corridor is extended from the northeast to south of Pakistan with geographical coordinates of 25° 24' to 36° 10' north latitude and 63° 21' to 74° 59' east longitude (Ullah et al., 2018). The CPEC consists of two major routes with an estimated length of 4918 km i.e., western route and eastern route. The western route covers northwestern parts of Pakistan including the Khyber Pakhtunkhwa and Baluchistan Provinces, while the eastern route passes through the southeastern parts of Pakistan and covering the major parts of the Punjab and Sindh provinces (Ullah et al., 2018). The CPEC project aims to connect the Kashgar city of China and the Gwadar Port of Pakistan (Javaid, 2016; Markey, 2016). Moreover, this corridor intends to promote regional connectivity across Pakistan with extensive networks of railways, highways, and pipelines accompanied by energy, industrial, and other infrastructure development projects (Esteban, 2016). As, the CPEC is extended from north to south of Pakistan and its networks of highways, railways, and industrial zones will be established across the entire country. Therefore, entire Pakistan is taken as a target region in the present study. Moreover, Pakistan is an autonomous country in the South Asian region with geographical coordinates of 23.6°–38° north latitude and 61°–78° east longitude. The country experiences high spatial variability in temperature due to multifarious and complex topography. The northern region experiences the coldest annual temperature (< 0 °C), while the central and southern parts of the country experience the highest annual average temperature (> 35 °C) (Gadiwala et al., 2013; Iqbal and Athar, 2018).

3. Materials and methods

3.1. Data

We used the monthly maximum (Tmax) and minimum (Tmin) temperature datasets of 48 stations for the period of 1980 to 2016. The data were obtained from the Pakistan Meteorological Department (PMD). The details of each weather station are provided in Fig. 1. The selection of the stations was done on the basis of their closeness to the CPEC routes, temporal coverage, data homogeneity, and completeness of the data record. Though, recent studies have stated that the use of gridded data is a good choice for detailed study of different climatic

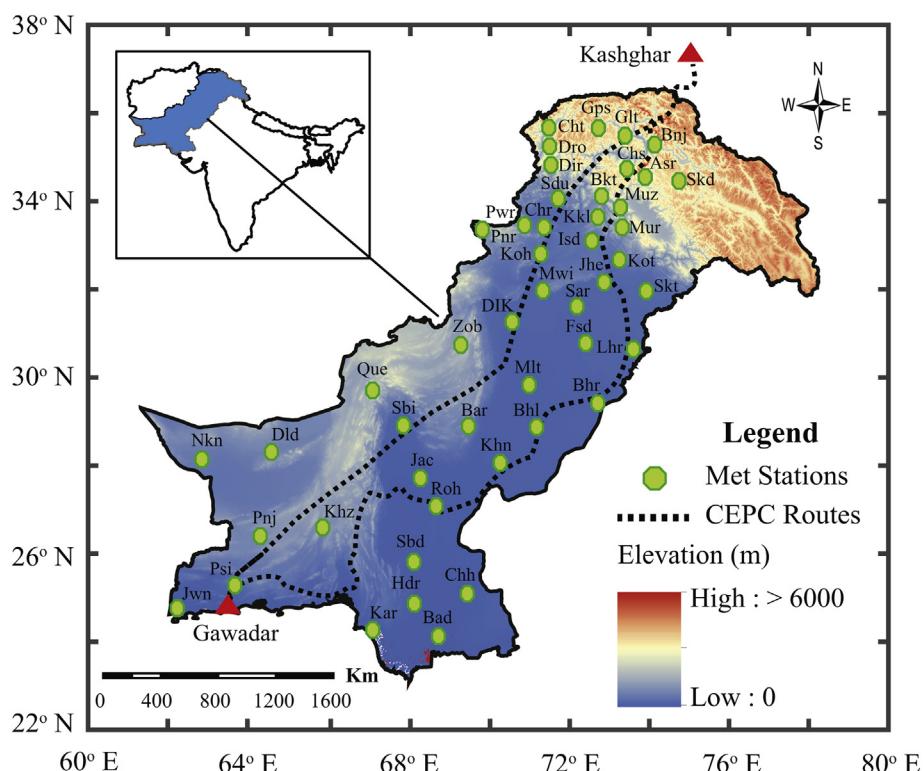


Fig. 1. Topographic map of the study area with CPEC routes and target meteorological stations.

factors in the target region (Ahmed et al., 2017; Khan et al., 2018); however, application of the gridded products for similar purposes is subject to validation in order to document their strengths and uncertainties (Laiti et al., 2018; Singh et al., 2017). Moreover, temperature variability and dynamics in diverse terrains and high altitudes are more complex, thus the applications of such gridded products from similar studies may produce uncertainties in the results (Henn et al., 2018; Shi et al., 2018a, 2018b; Walton and Hall, 2018). Sometimes, the gridded data tend to underestimate or overestimate the frequency and intensity of climatic factors, which ultimately may affect their long-term tendency in a region with multifarious topography (Hofstra et al., 2010; King et al., 2013). Due to these reasons, we used the long-term observed data with relatively high stations' density in complex terrains and elevated regions. Moreover, we also ensured the quality of the data by using autocorrelation and pre-whitening methods.

The Tmax and Tmin trends were assessed on seasonal and annual basis. The desired seasons were defined as follows: winter (December – February), spring (March – May), summer (June – August), and autumn (September – November) (Fowler and Archer, 2006). The seasonal and annual datasets of Tmax and Tmin were obtained by averaging the monthly values of Tmax and Tmin, respectively. Similarly, the regional averages of Tmax and Tmin for seasonal and annual time series were calculated by taking the average values of all the target stations.

3.2. Descriptive statistics

Before applying the Mann-Kendall (MK), Sen's Slope (SS) estimator and Sequential Mann-Kendall (SQMK) tests, the degree of autocorrelation was checked in Tmax and Tmin time series using the autocorrelation test (Ahmad et al., 2015; Khattak and Ali, 2015; Ullah et al., 2018). After that, the non-parametric MK test (Kendall, 1955; Mann, 1945) was applied to detect the significance of monotonic trend. The MK test is sensitive to the presences of autocorrelation in the time series, which may affect the outcomes of the MK test (Salman et al., 2017), while the modified Mann Kendall Test (m-MK) is effective to

account the effect of autocorrelation (Hamed and Rao, 1998; Khan et al., 2018). However, to overcome the problem of autocorrelation using the MK test, the pre-whitening approach can be applied (Ahmad et al., 2015; Qasim et al., 2016). Therefore, the present study prefers the MK test over the m-MK version as the autocorrelation was removed from the datasets using the pre-whitening method. Moreover, the MK test is simple and robust against outliers, missing values, normal distribution, and is less sensitive to abrupt breaks in time series (Ahmed et al., 2017; Salman et al., 2017; Zamani et al., 2017). Similarly, the SS estimator test (Sen, 1968) was used to determine the slope of the trend in Tmax and Tmin (Gocic and Trajkovic, 2013; Sonali and Kumar, 2013). Moreover, the SQMK test (Sneyers, 1990) was used to detect the abrupt changes in Tmax and Tmin trends over time (Chatterjee et al., 2014; Some'e et al., 2012). Similarly, the least square method was employed to calculate the linear trends, while the 2-tailed simple *t*-test was used to determine the significance of the linear trends in Tmax and Tmin time series (Casella and Berger, 2002; Moore and McCabe, 2003; Sun et al., 2017). These statistical methods are briefly discussed in recent research papers (Ullah et al., 2018; Xu et al., 2018).

4. Results

4.1. Testing and removal of autocorrelation

Fig. 2 shows the serial correlation coefficients of the Tmax and Tmin time series for seasonal and annual time scales. The time series are tested at different lags using autocorrelation test (Ahmad et al., 2015; Ullah et al., 2018). The analysis represents that most of the time series are independent with no significant serial correlation at lag-1. However, few datasets of Tmax and Tmin for seasonal and annual time scales have been detected with significant positive autocorrelation at lag-1. In Tmax, significant autocorrelations have been observed in spring and annual time series, while in Tmin the spring, summer and annual datasets have been detected with significant positive autocorrelation at lag-1. The presences of significant autocorrelation may

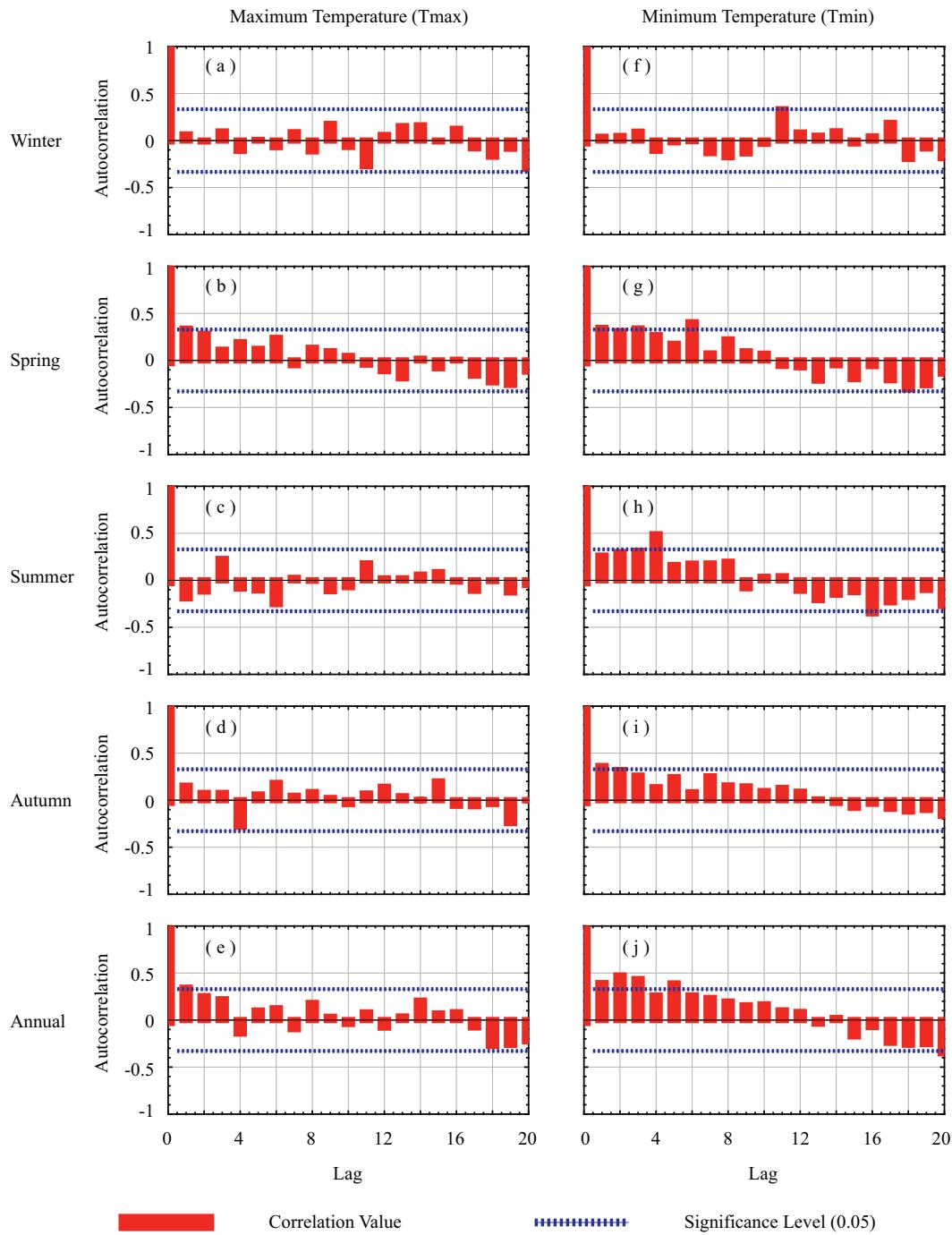


Fig. 2. Autocorrelation of Tmax and Tmin time series for seasonal and annual scale under different lags; (a) Tmax winter, (b) Tmax spring, (c) Tmax summer, (d) Tmax autumn, (e) Tmax annual (f) Tmin winter, (g) Tmin spring, (h) Tmin summer, (i) Tmin autumn, (j) Tmin annual.

affect the outcomes of MK test, therefore, pre-whitening approach was employed to avoid the effects of autocorrelation on MK test (Khattak and Ali, 2015). All the significant autocorrelations were removed from the relevant time series using Eqs. (1) and (2).

4.2. Climatology of the region

Fig. 3 represents the long-term annual Tmean and monthly Tmax, Tmin and Tmean of the study area. The spatial distribution of temperature indicates that there is a high variability both at latitude and longitudes. The northern and southwestern mountainous region are dominated by a humid climate with mean annual temperature ranges

from 0 to 20 °C. Similarly, the central and eastern parts of the country are covered by Indus plains with a tropical climate and mean annual temperature ranges from 21 to 25 °C. The southern coastal belt is dominated by coastal climate with mean annual temperature ranges from 26 to 30 °C. Moreover, the long-term monthly means of maximum, minimum and mean temperature of the study area indicate that January is the coldest month while July is the hottest month of the year. In January, the lowest observed values for long-term maximum, minimum, and mean temperatures are 16 °C, 4 °C, and 10 °C, respectively. Similarly, in the month of July, the highest observed values for long-term maximum, minimum and mean temperature are 37 °C, 22 °C and 30 °C. Similar results were reported by previous studies (Asmat

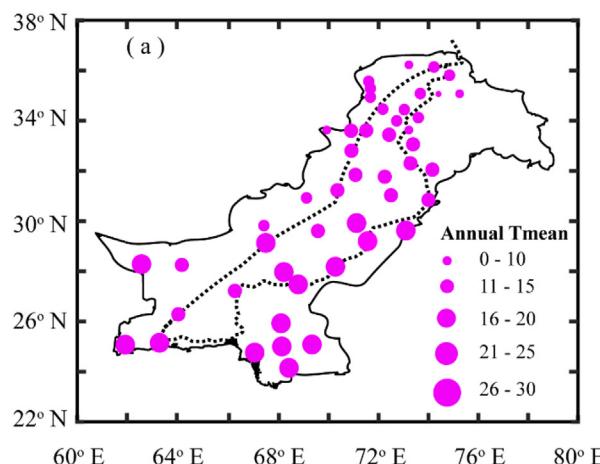


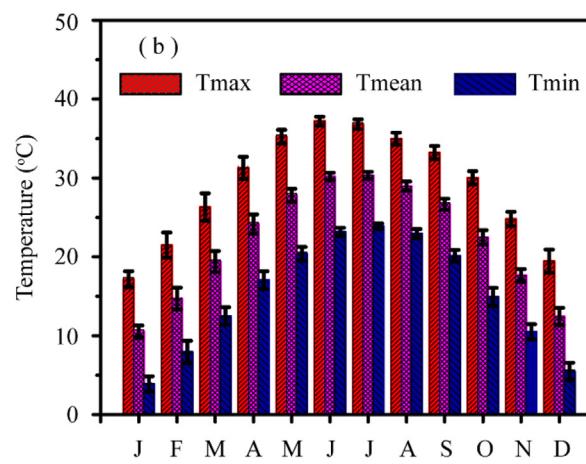
Fig. 3. Climatological annual and monthly means of T_{max} , T_{min} and T_{mean} of the study region during 1980–2016; (a) annual T_{mean} , (b) monthly means of T_{max} , T_{min} and T_{mean} . The vertical bars represent the standard deviations of the T_{max} , T_{min} and T_{mean} .

et al., 2017; Iqbal et al., 2016; Iqbal and Athar, 2018).

4.3. Spatiotemporal variations of annual and seasonal Tmax

The temporal (Fig. 4 a-e) and spatial (Fig. 5 a-e) variations of seasonal and annual Tmax for the CPEC region are shown. The analysis indicates that Tmax has been increased in all seasons and on annual scales with a sharp increase in spring and annual time scales. However, a rapid increase was noticed in all seasonal and annual temperatures during the period of 1997–2000. The country has faced a drought and hot period during 1997–2002 (Abbas et al., 2014; Islam et al., 2009; Rahman et al., 2018). Thus, this sharp increase in seasonal and annual Tmax could be the result of that drought and hot period experienced by major parts of the country. This drought was considered as one of the severe and long-lasting droughts in the history of Pakistan (Shafiq and Kakar, 2007; Xie et al., 2013). Moreover, the trend of Tmax increased significantly at the rates of 0.22, 0.37, 0.20, 0.23, and 0.31 °C per decade in winter, spring, summer, autumn, and annual time scales, respectively (Table 1). The results are in agreement with the findings of previous studies. Khan et al. (2018), found a slight positive trend in winter, spring, summer, autumn, and annual temperatures at the rates of 0.16, 0.37, 0.18, 0.25, and 0.23, respectively. Similarly, Iqbal et al. (2016), also found a positive trend in all seasons and annual temperatures except summer season. The increasing trend of annual Tmax was detected in the Indus River basin at the rate of 0.59 °C per decade (Khattak et al., 2011). Qasim et al. (2016), also reported a positive trend of 0.12 °C per decade in annual Tmax over Pakistan. Though, these studies have detected trends with different magnitudes, which could be the results of different time scales or different statistical tools (Khan et al., 2018; Liebmann et al., 2010). The results of this study indicate that the annual Tmax of Pakistan was increased double (0.31 °C per decade) as compared to the global average increase of 0.15 °C/decade. The sharp increase in seasonal and annual Tmax has significantly affected the society with frequent temperature extremes in recent years.

The spatial distribution of seasonal and annual Tmax trends illustrates that the whole country has experienced pronounced warming during the study period. In winter season, most of the stations exhibited a positive trend with steep trend in the northern mountainous region. The MK results showed that the positive trend was significant at 20 stations at 95% confidence level. The maximum positive trend magnitude was detected at Chitral (0.42 °C per decade), Zhob (0.41 °C per decade) Astore, Balakot, Gilgit, and Murree (0.42 °C per decade). The results concur the findings of the previous studies (Bhutiyani et al., 2007; Bocchiola and Diolaiuti, 2013). They reported an increasing



trend (0.17 °C per decade) in winter Tmax over the northern mountainous region of Pakistan. Moreover, Khan et al. (2018) also found a positive trend of 0.39 °C per decade in the northern parts of the country. Khattak et al. (2011) reported that the trend of winter Tmax increased sharply at the rates of 1.79 °C per 39 years over the upper Indus River basin of Pakistan (Khattak et al., 2011). Similarly, a slight positive trend was detected in winter Tmax over the upper Indus River basin (Rahman and Dawood, 2017; Rauf et al., 2016). Irrespective of the whole country, few stations located in the upper plain and northwestern mountainous regions were detected with a negative trend. The negative trend was significant at one station with 0.05 significance level. The highest negative trend was detected at Parachinar (-0.37 °C per decade), Lahore (-0.35 °C per decade) and Sargodha (-0.31 °C per decade) stations. These results are in agreement with the findings of recent past studies (Ahmad et al., 2014; Iqbal et al., 2016; Khattak and Ali, 2015). They reported a negative trend of -0.31 and -0.30 °C per decade in winter Tmax over upper plain areas of Pakistan, respectively. On the other hand, the results deny the findings of Zahid and Rasul (2012) and Khalid et al. (2013), who reported an increasing trend in winter Tmax over the said region. Similarly, Khan et al. (2018) found a positive trend of 0.13 °C per decade in Tmax of the winter season over the lower northern plains. Khattak et al. (2011) also noticed a positive trend (1.66 °C per 39 years) in winter Tmax for the said region.

In spring season, the increasing trend of Tmax was obvious over the whole country with a sharp increase in the northern mountainous region and southern coastal belt. All the stations exhibited positive trend maximum with a sharp increase at Balakot, Chitral, Dalbandin, Hyderabad, Murree, Panjgur, and Zhob stations at the rates of 0.42, 0.48, 0.45, 0.41, 0.48, 0.47, and 0.48 °C per decade, respectively. The MK test results indicate that 28 stations exhibited significant positive trends at 0.05 significance level. The results affirm the findings of previous studies. Iqbal et al. (2016) reported an increasing trend (1.00 °C per decade) in spring Tmax over most parts of the country with a maximum increase in the northern region. Khan et al. (2018) noticed a sharp positive trend in spring Tmax over the whole country. Similarly, Sajjad et al. (2009) found a sharp increasing trend (0.77 °C per decade) in Tmax across the southern belt of Pakistan. Several more studies have also reported a warming trend in the central and southern regions of Pakistan (Abbas, 2013; Abbas et al., 2018a; Khattak and Ali, 2015; You et al., 2017). It is noteworthy that the increasing trend of spring Tmax contributes a large fraction to the annual Tmax trend (0.37 °C per decade), which is in line with the findings of Iqbal et al. (2016).

The spatial analysis of summer Tmax indicates a pronounced warming trend across the whole country with a significant positive trend at 24 stations. However, the magnitude of positive trend was high

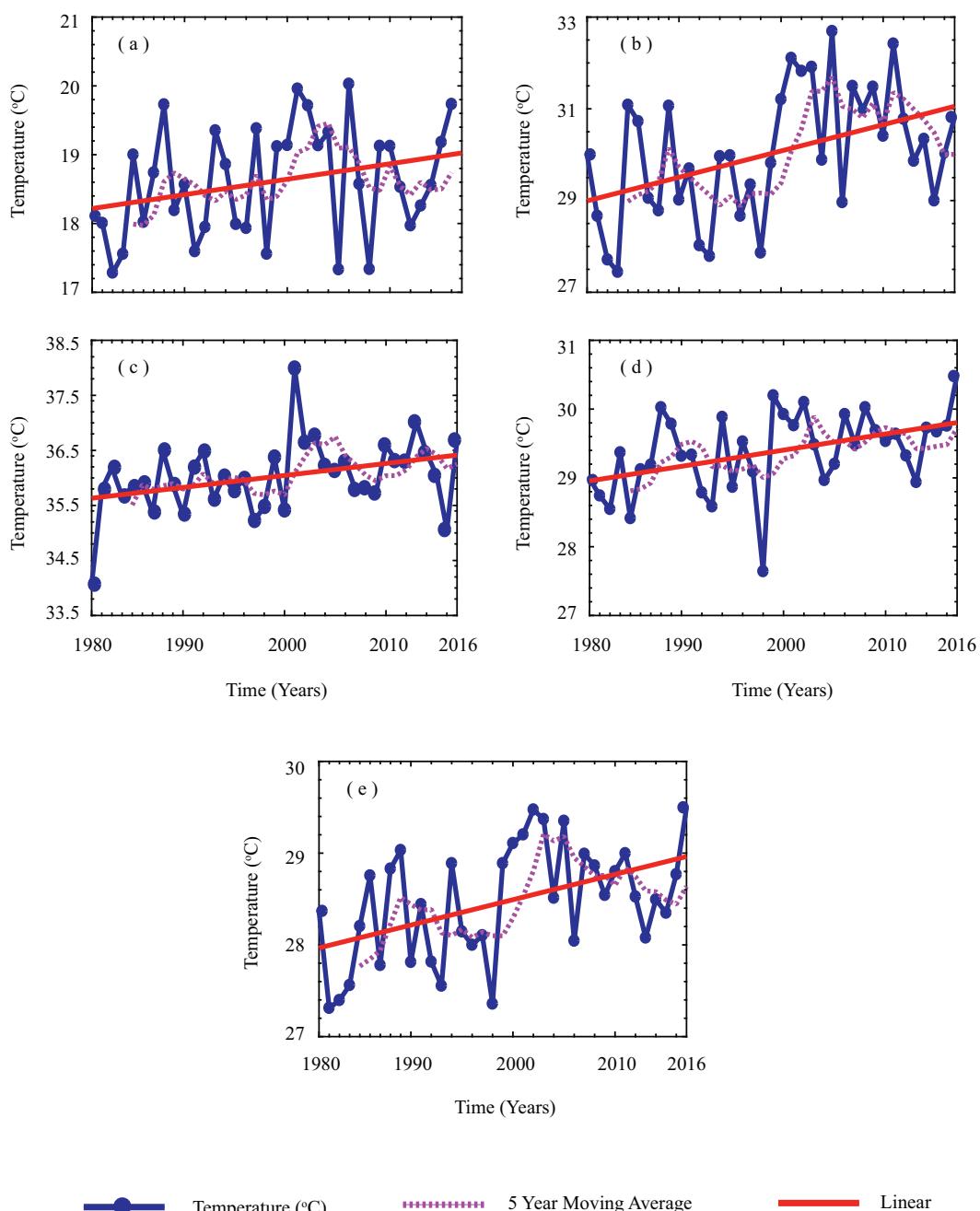


Fig. 4. Temporal variation and linear trend of seasonal and annual Tmax over the CEPC region during 1980–2016; (a) winter, (b) spring, (c) summer, (d) autumn, (e) annual.

in the northern region with maximum trends at Astore (0.49°C per decade), Chilas (0.41°C per decade), Gilgit (0.46°C per decade), and Skardu (0.45°C per decade) stations. The results affirm the findings of Bhutiyani et al. (2007), who reported a positive trend of 1.3°C in summer Tmax over northern Pakistan during the last century. Over the last few decades, summer Tmax has been increased by 0.16°C per decade in the Hindu Kush Himalayan region (Ren et al., 2017). Similarly, a slight increasing trend of 0.60°C per decade, was detected over the northern mountainous region (Khan et al., 2018). Similarly, Khattak et al. (2011) stated that the stations located in the middle and lower Indus River basin experienced a warming trend in summer Tmax. During the last century, the southern belt of Pakistan experienced the highest warming trend reported by You et al. (2017). However, some studies reported a decreasing trend in summer Tmax over the southern parts of the country, which contradict our results. Iqbal et al. (2016)

found a negative but non-significant trend in summer Tmax over different parts of the country. Despite the whole country, three stations located in the monsoon core region exhibited a significant negative trend. The highest negative trend slope was recorded at Lahore and Sargodha stations at the rate of -0.33 and -0.27°C per decade, respectively. The results confirm the findings of Iqbal et al. (2016) and Khattak and Ali (2015), who reported a slight decreasing trend of -0.043 and -0.13°C per decade in the said region, respectively.

The trend analysis of autumn Tmax showed that the warming trend was obvious over the entire region. However, the magnitude of the positive trend was high in northern and southwestern mountainous regions. According to the MK test, the positive trend was significant at 25 stations with 95% confidence level. The maximum positive trend slope was observed at Astore, Chitral, Dalbandin, Murree, and Zhob stations with 0.46 , 0.45 , 0.44 , 0.45 , and 0.44°C per decade,

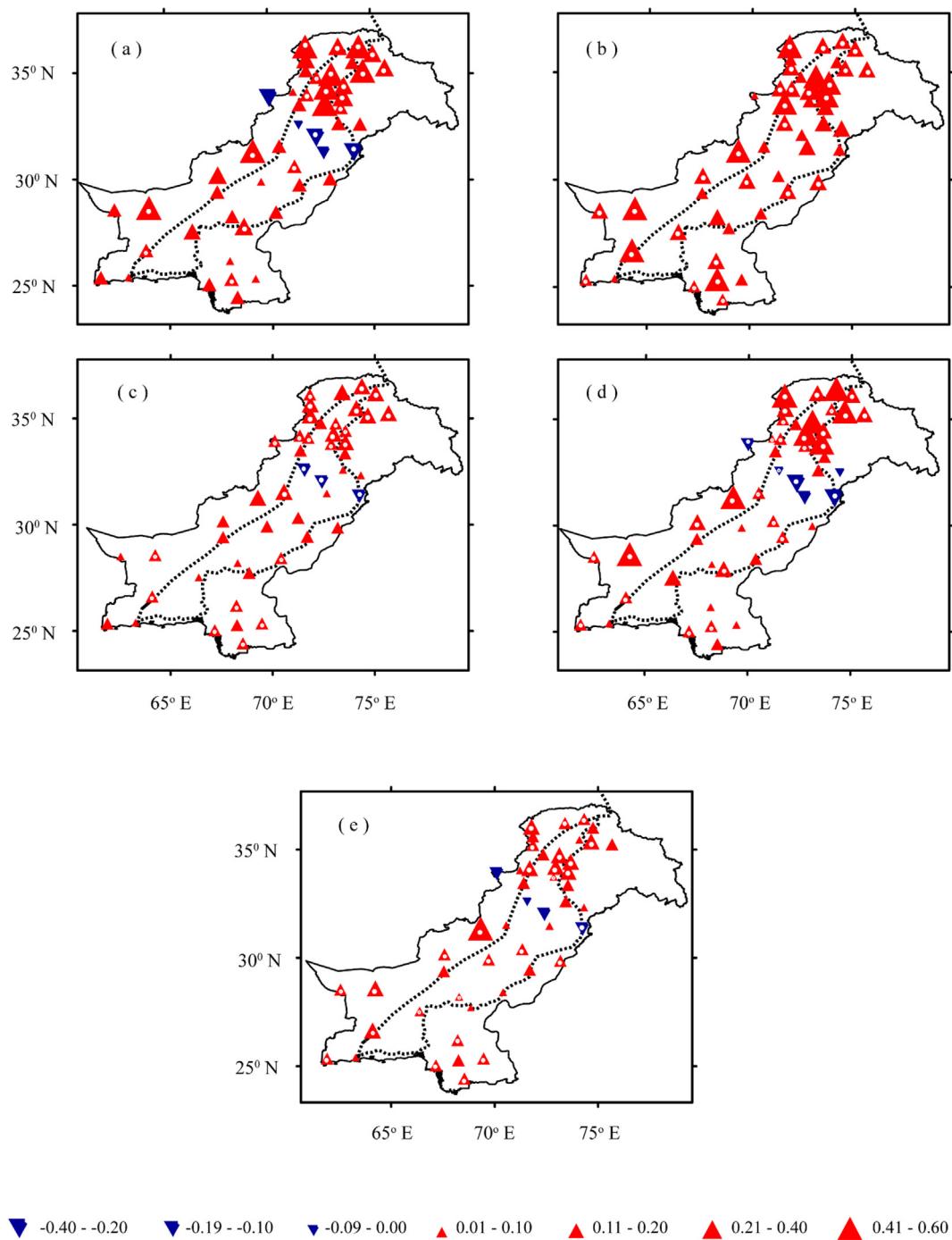


Fig. 5. Spatial distribution of seasonal and annual Tmax over the CPEC region during 1980–2016; (a) winter, (b) spring, (c) summer, (d) autumn, (e) annual. Upward pointing red triangles show increasing trends, downward pointing blue triangles represent decreasing trends (unit: °C per decade). The white dots indicate statistically significant trends at $\alpha = 0.05$ significance level. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Long-term trend analysis of Tmax and Tmin on seasonal and annual time scales.

Time scale	Tmax	Ho	Tmin	Ho	Unit
Winter	0.22	R	0.33	R	°C per decade
Spring	0.37	R	0.39	R	°C per decade
Summer	0.20	R	0.25	R	°C per decade
Autumn	0.23	R	0.27	R	°C per decade
Annual	0.31	R	0.36	R	°C per decade

Ho: Null Hypothesis, R: Rejected.

respectively. The results confirm the findings of Khattak et al. (2011), who reported a significant increase in autumn Tmax over upper and lower Indus River basin. Similarly, Subash and Sikka (2014) noticed a positive trend ($0.67\text{ }^{\circ}\text{C}/100\text{ years}$) in autumn Tmax over the western Himalayan region. The results also affirm the findings of Iqbal et al. (2016), who detected a sharp increase in autumn Tmax over the northern mountainous region of Pakistan. Moreover, Khan et al. (2018) reported an increasing trend of $0.32\text{ }^{\circ}\text{C}$ per decade, in autumn Tmax in the different climatic zones of Pakistan. Irrespective of the entire country, some of the stations located in the middle Indus River basin

exhibited a negative trend in autumn Tmax. The negative trend was significant at 4 stations at 95% confidence level. The highest negative trend values were detected at Sargodha and Lahore stations with -0.31 and -0.34 °C per decade, respectively. These results are in line with the findings of previous studies (Khattak and Ali, 2015; Sadiq and Qureshi, 2010). They reported a decreasing trend of -0.40 and -0.41 °C per decade in the said region, respectively.

The trend of annual scale Tmax has shown an obvious increase over the whole country. Similar to seasonal Tmax, the stations located in the northern and southwestern mountainous region of the country exhibited sharp positive trends in annual Tmax. The maximum slope of the positive trend was recorded at Chitral (0.36 °C per decade), Dalbandin (0.34 °C per decade), Murree (0.36 °C per decade), and Zhob (0.41 °C per decade) during the study period. The MK test results indicate that 26 stations exhibited a significant positive trend at 0.05 significance level. The results are in agreement with the findings of previous studies. Khan et al. (2018) and Iqbal et al. (2016) reported a sharp increasing trend of 0.29 and 0.32 °C per decade over the study area, respectively. Similarly, Qasim et al. (2016) found a positive trend of 0.36 °C in Pakistan during the period of 1976–2005. Several studies also stated that the northern mountainous belt of Pakistan experienced a significant warming trend during the last century (Dharmaveer et al., 2015; Revadekar et al., 2013; Subash and Sikka, 2014). Regardless of the entire country, some of the stations located in the northern plain areas exhibited a negative trend; however, the negative trend was significant at one station. The highest negative trend values were detected at Lahore, Sargodha and Parachinar stations with -0.26 , -0.16 and -0.14 °C per decade, respectively.

4.4. Spatiotemporal variations of annual and seasonal Tmin

The temporal (Fig. 6 a-e) and spatial (Fig. 7 a-e) variations of Tmin on seasonal and annual times scales for the CPEC region are shown. The temporal analysis of Tmin represents that all seasonal and annual temperatures exhibited significant positive trends during the study period. However, a steep increase was found in spring season followed by annual and winter. The trend of winter, spring, summer, autumn, and annual Tmin linearly increased at the rates of 0.33, 0.39, 0.25, 0.27, and 0.36 °C per decade, respectively (Table 1). The results indicate that Tmin is rising faster than Tmax in all seasons and on annual scale, which is in line with the findings of recent studies conducted at local, regional and global levels (Grotjahn et al., 2016; Jhajharia and Singh, 2011; Rauf et al., 2016; Ren et al., 2017; Sayemuzzaman et al., 2015; Shahid et al., 2012). Similarly, several studies have reported positive trends in seasonal and annual Tim over the study region. Khan et al. (2018) found a positive trend in winter, spring, summer, autumn, seasonal and annual Tmin with 0.41, 0.37, 0.32, 0.39, and 0.37 °C per decade, respectively. The results also concur with the findings of Qasim et al. (2016) and Iqbal et al. (2016), who reported an increasing trend in seasonal and annual Tmin over different zones of Pakistan. Moreover, the long-term analysis of Tmin time series showed that a rapid increase has been detected in all seasons and on an annual scale during the period of 1998–2001 (Fig. 6 a-e). The rapid increase in Tmin during the said period indicated that the study area has experienced a warming trend during this period. These findings are also supported by previous studies as a long-lasting and severe drought has been reported in Pakistan during 1998–2002 (Rahman et al., 2018; Xie et al., 2013). This drought was considered one of the catastrophic droughts in the history of Pakistan (Shafiq and Kakar, 2007). Therefore, it can be concluded that the rapid increase during 1998–2001 could be the result of prolonged drought and hot period in the country.

The spatial analysis of Tmin indicates that warming pattern was obvious both in seasonal and annual time scales over the whole country. In winter season, a noticeable increase was detected in Tmin with a significant positive trend at 14 stations. A sharp increase was recorded in the central and southwestern parts of the country. The

highest positive trend slope was recorded at Barkhan and Zhob stations with 0.47 and 0.46 °C per decade, respectively. Similar results were reported by previous studies (Iqbal et al., 2016; Khan et al., 2018). They reported an increasing trend of 0.45 and 0.41 °C per decade, respectively. There were only three stations (Parachinar, Dalbandin and Skardu) located in the northwestern region exhibited a negative trend during the study period. The highest negative trend was detected at Parachinar station with -0.34 °C per decade during the study period. The result concurs with the findings of Iqbal et al. (2016), who reported a non-significant decreasing trend (-0.30 °C per decade) for the said region.

In spring season, the trend of Tmin exhibited a pronounced warming with sharp magnitude in central, southwestern and southeastern regions of the country. The highest positive trend was observed at Khanpur, Lahore, Mianwali, Quetta, Rohri, Sialkot, and Zhob stations with 0.49, 0.51, 0.50, 0.49, 0.49, 0.48, and 0.49 °C per decade, respectively. The MK test results indicate that 28 stations exhibited a significant positive trend at 0.05 significance level. The results are in agreement with the findings of Khan et al. (2018) who reported a significant positive trend (0.16–0.37 °C per decade) in major climatic zones of Pakistan. According to Qasim et al. (2016), Tmin is increasing at the rates of 0.49 and 0.61 °C per decade, over the central and southern parts of the country, respectively. On the other hand, Khattak et al. (2011) reported a decreasing trend in the upper, middle and lower Indus River Basin in Tmin. In spring season, Parachinar was the only one station with a significant negative trend at the rate of -0.37 °C per decade during the study period.

Similar to spring Tmin, the spatial distribution of trend for summer Tmin represents an obvious increasing trend over the whole country; however, the magnitude of the trend for summer Tmin was lower than spring Tmin. The southwestern and southeastern zones exhibited a sharp increase in summer Tmin. The maximum positive trend values were recorded at DI Khan, Khanpur, Quetta, Rohri, and Zhob at the rate of 0.48, 0.47, 0.49, 0.50, and 0.48 °C per decade, respectively. According to the MK test, the trend was significant at 25 stations with 95% confidence level. The results affirm the findings of Khan et al. (2018) and Iqbal et al. (2016) who reported an increasing trend of 0.48 and 0.50 °C per decade over different regions of the country, respectively. On the other hand, our results contradict the findings of Khattak et al. (2011), who reported a decreasing trend of summer Tmin over major parts of Pakistan. Parachinar was the only station which showed an insignificant negative trend of -0.34 °C per decade, for summer Tmin during the study period.

During autumn Tmin, a positive trend was apparent over the whole country with a maximum trend in the eastern and southern parts. The highest values of positive trend were observed at Chhor, Karachi, Khanpur, Lahore, and Rohri stations at the rate of 0.43, 0.45, 0.43, 0.44 °C per decade, respectively. The trend was significant at 28 stations, out of which 27 stations exhibited a significant positive trend at 0.05 significance level. The results affirm the findings of Qasim et al. (2016), who reported an increasing trend of 0.29 °C per decade in Tmin over the study area. Khan et al. (2018) also noticed an increase of autumn Tmin with 0.39 °C per decade in the study area. Despite the whole country, few stations (Parachinar and Dalbandin, and Skardu) located at high altitudes experienced a decreasing trend during the study period. The maximum slope of the negative trend was detected at Parachinar (-0.31 °C per decade) during 1980–2016. Our results are consistent with the findings of Khattak et al. (2011); Iqbal et al. (2016); Rahman and Dawood (2017), who reported a decreasing trend in the said region. However, Ahmad et al. (2014b) and Khattak and Ali (2015) reported an increasing trend (0.32 °C per decade) for this climatic zone, which contradicts our findings.

The spatial analysis of Tmin at the annual scale indicates that the positive trend has a similar pattern to autumn. It means that the entire study region has experienced a warming trend during 1980–2016 with a sharp positive trend in the southeastern parts of the country. The

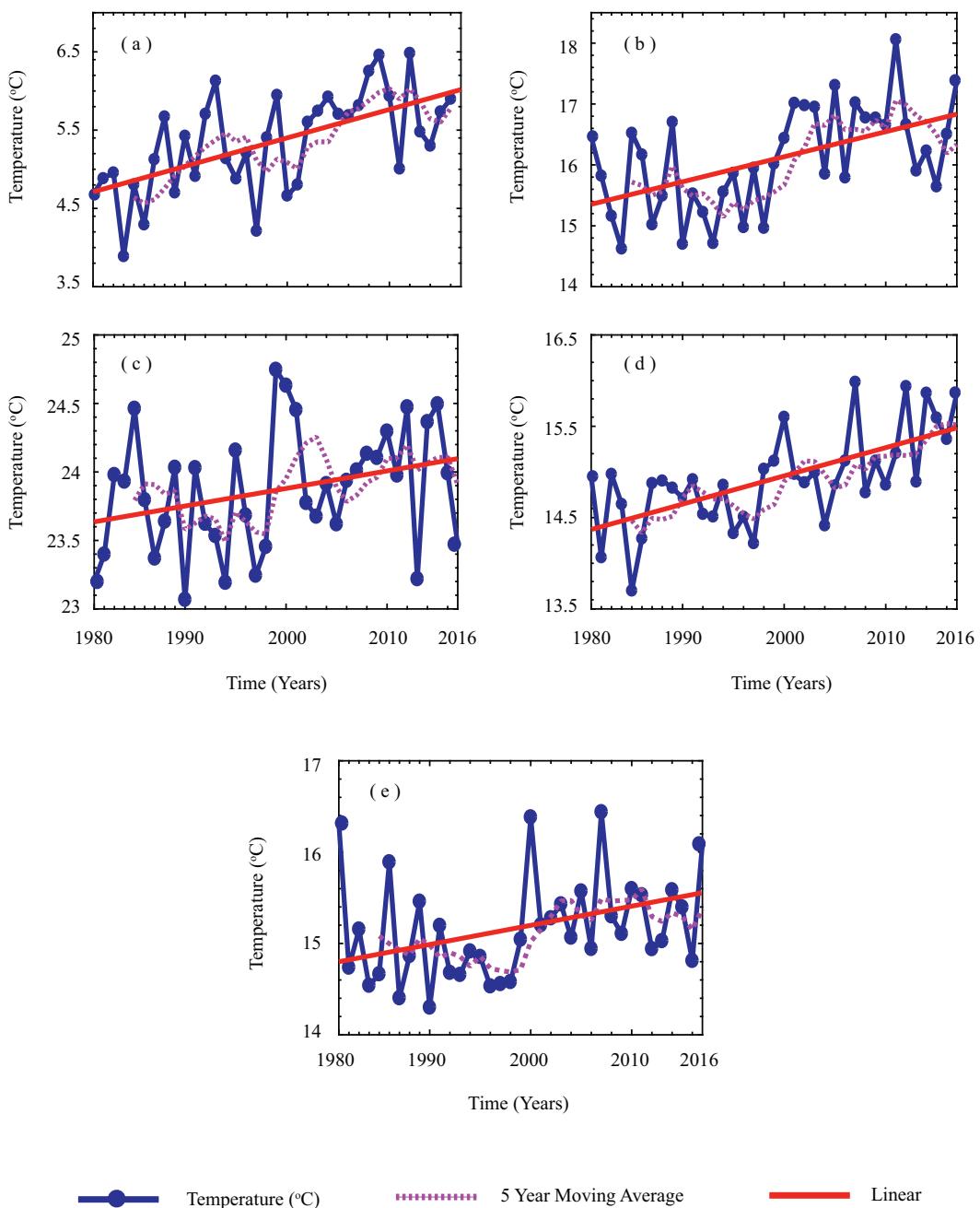


Fig. 6. Similar to Fig. 4, but for T_{\min} .

maximum values of positive trend were observed at Khanpur, Lahore and Rohri stations at the rate of 0.47, 0.48, 0.50 °C per decade, respectively. According to the MK test results, the trend was significant at 35 stations, out of which 34 stations exhibited a significant positive trend at 95% confidence level. These results are consistent with the findings of previous studies (Abbas et al., 2018b; Iqbal et al., 2016; Khan et al., 2018; Khattak and Ali, 2015). Khattak et al. (2015) noticed an increasing trend of 0.25 °C per decade, in annual Tmin in Punjab province. Similarly, Iqbal et al. (2016) reported a positive trend of 0.32 °C per decade, in annual Tmin over the whole country. According to Khan et al. (2018), the trend of annual Tmin has been increasing at the rate of 0.17–0.37 °C per decade over Pakistan. Similar to autumn Tmin, some of the stations located in the northern and southwestern mountainous regions exhibited a negative trend. These stations include Dalbandin, Parachinar and Skardu. The highest negative value of trend was detected at Parachinar station with –0.35 °C per decade during the

study period. These results affirm the findings of previous studies (Abbas et al., 2018b; Iqbal et al., 2016; Khattak et al., 2011; Rahman and Dawood, 2017). They reported a decreasing trend in annual Tmin over the northern and southwestern mountainous regions of Pakistan.

4.5. Mutation of seasonal and annual Tmax and Tmin

The rapid change in climate indicates the transition of climate from one stable to another (Ullah et al., 2018; Xu et al., 2018). This abrupt shift in climate when the climatic system crosses the threshold level due to some external factors, and activates a change to a new state at a rate determined by the climate system (Matyasovszky, 2011; Rashid et al., 2015; Sonali and Kumar, 2013). The SQMK test was employed for the first time to detect mutation points in temporal trends of seasonal and annual Tmax and Tmin in the study area. The progressive and retrograde series were obtained at 0.05 significance level. The results of

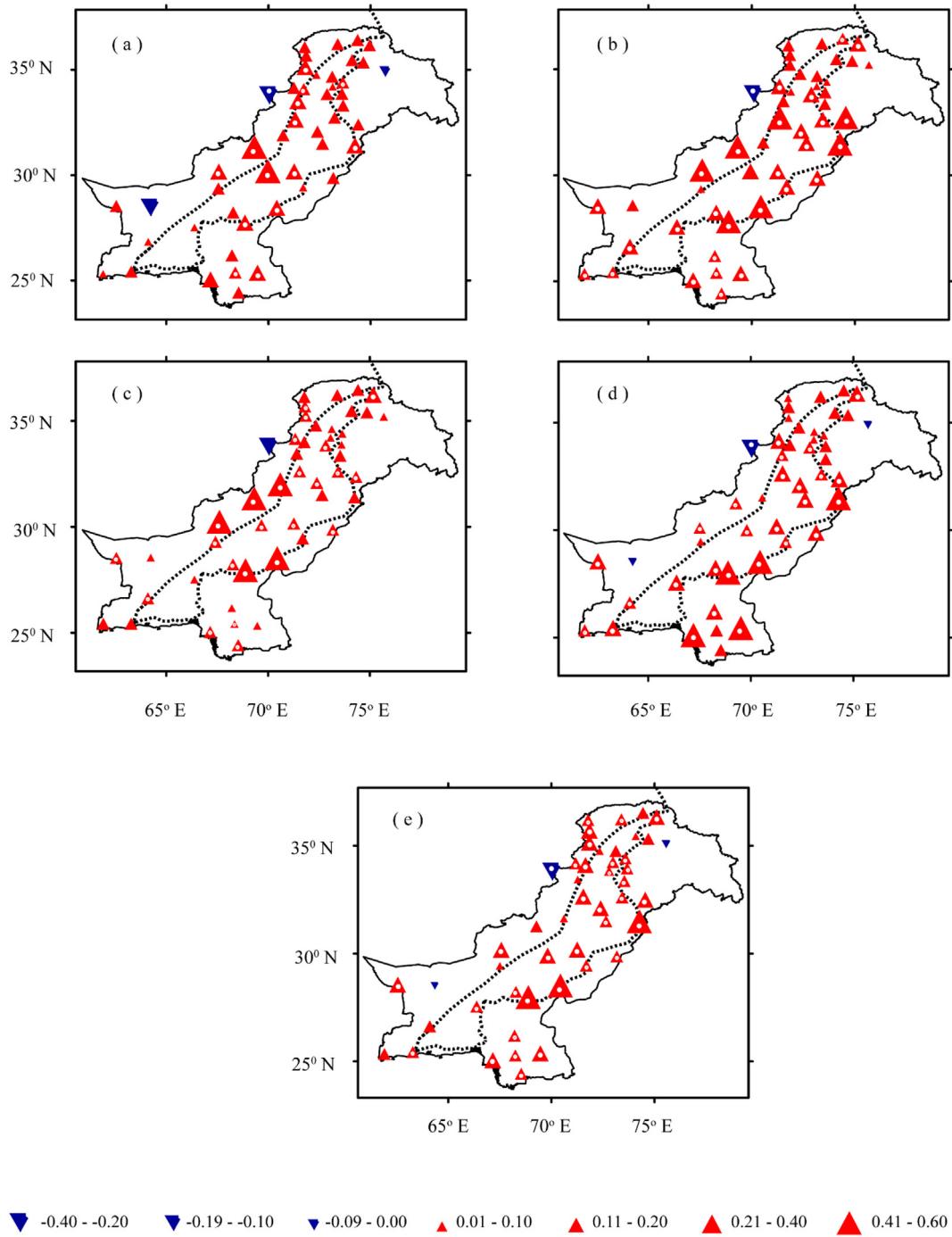


Fig. 7. Similar to Fig. 5, but for Tmin.

rapid changes in seasonal and annual Tmax trends are shown in Fig. 8. The analysis indicates that the winter season has experienced a series of the gentle downward trend during the period of 1983–1985. Similarly, in the spring season, three mutation points were observed during the study period. A significant negative shift was detected in 1985 followed by a neutral mutation in 1996 and a sharp positive in 2002. In summer Tmax trends, a series of continues gentle positive mutation was noticed during 1998–2001. Similar to summer Tmax, autumn time series also showed a chain of slight positive shift during the period of 1997–1999. On the annual scale, the Tmax time series exhibited two mutation points in the late 1990s. Firstly, a gentle upward shift was noticed in 1997 followed a sharp positive change in 2000.

The results of abrupt mutations in seasonal and annual Tmin time

series are shown in Fig. 9. The analysis represents that the mutation in winter trend was earlier than in other seasons. In winter, a negative abrupt shift was noticed in 1985 with an upward movement of progressive series. The trend of spring Tmin showed more rapid and complex changes between 1995 and 2009. A steep negative shift was detected in 1995 followed by a series of sharp positive mutations. In spring season, the initial two non-significant positive shifts were noticed in 2002 and 2006 followed by a significant positive mutation in 2009. In summer Tmin, two mutation points were detected during the study period. A steep downward shift was observed in 1997 followed a sharp positive shift in 1999. Similarly, the autumn time series of Tmin exhibited two mutation point. An abrupt negative change was found in 1996 followed a sharp positive change in 1998. The annual Tmax also

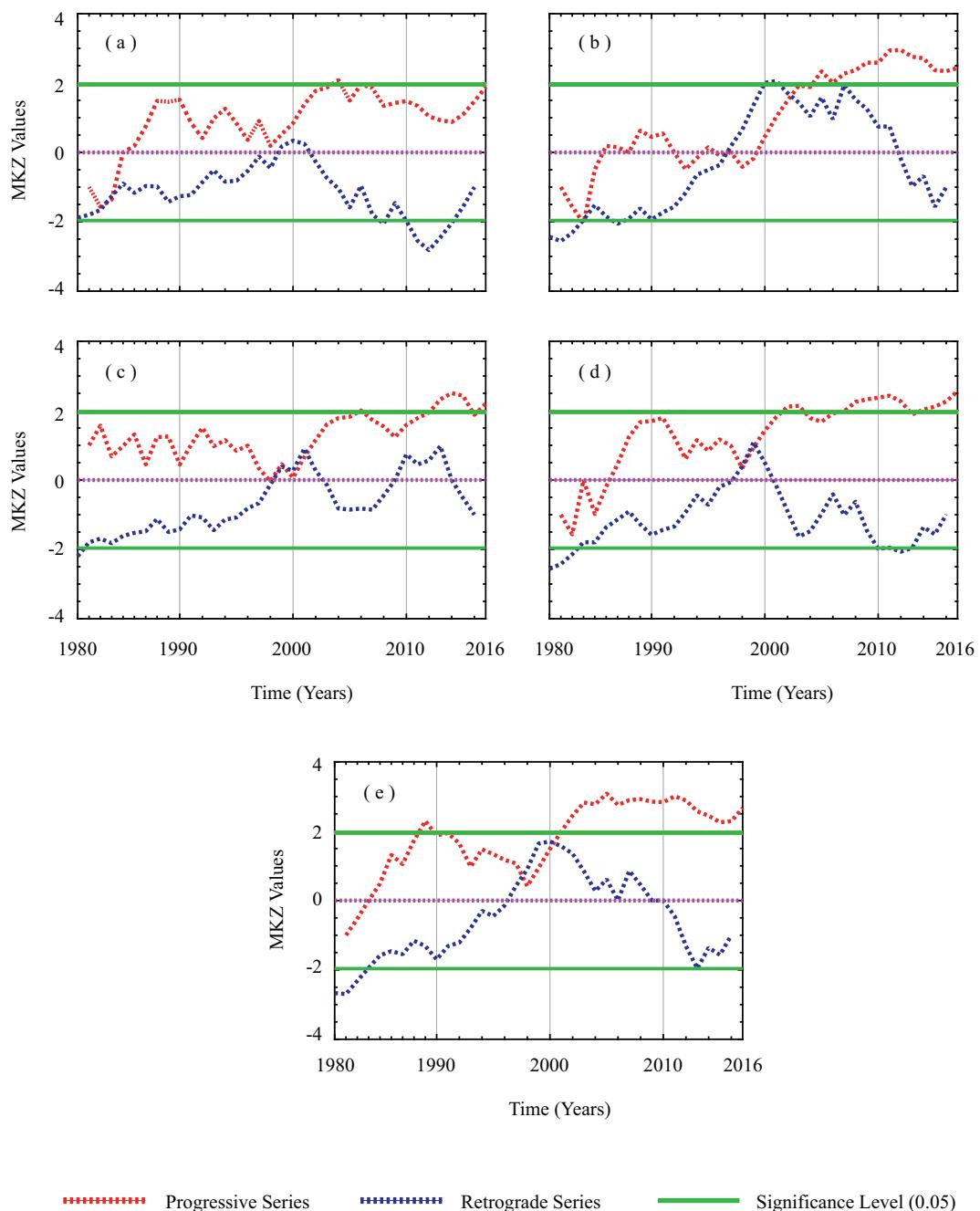


Fig. 8. Abrupt changes of seasonal and annual Tmax over the CPEC region trend during 1980–2016; (a) winter, (b) pre-monsoon, (c) monsoon, (d) post-monsoon, (e) annual.

shows that two mutation points during the study period. A steep downward shift was detected in 1997, while a sharp positive change was found in 2001.

Overall, the analysis of seasonal and annual time series of Tmax and Tmin indicates that most of the abrupt changes have occurred during the period of 1995–2010. In the Tmax time series, the abrupt changes were occurred during 1997–2002, while in Tmin trends, the sharp changes were found during 1995–2009. Except for winter season of Tmax and Tmin, all the time series showed abrupt and complex mutations in the late 1990s and early 2000s, which indicates that this was the crucial period in terms of temperature variations in the study area. Moreover, the linear trends of Tmax and Tmin for seasonal and annual scales also showed sharp and dynamic changes during this period, which are in line with the abrupt mutation points noted here. Many

studies reported that the country has experienced a hot period with severe drought during the late 1990s, which could be the outcome of abrupt mutations in Tmax and Tmin during this time period (Shafiq and Kakar, 2007; Xie et al., 2013). According to Abbas et al. (2014), an extreme high temperature in combination with low rainfall for a long period (1999–2002) resulted in drought over different parts of Pakistan (Abbas et al., 2014; Rahman et al., 2018).

5. Discussions

The increase in seasonal and annual Tmax and Tmin could be the outcomes of topographic factors, rapid urbanization, deforestation, population expansion or/and other anthropogenic factors (Balling et al., 2016; Roy et al., 2016). In recent decades, several studies have

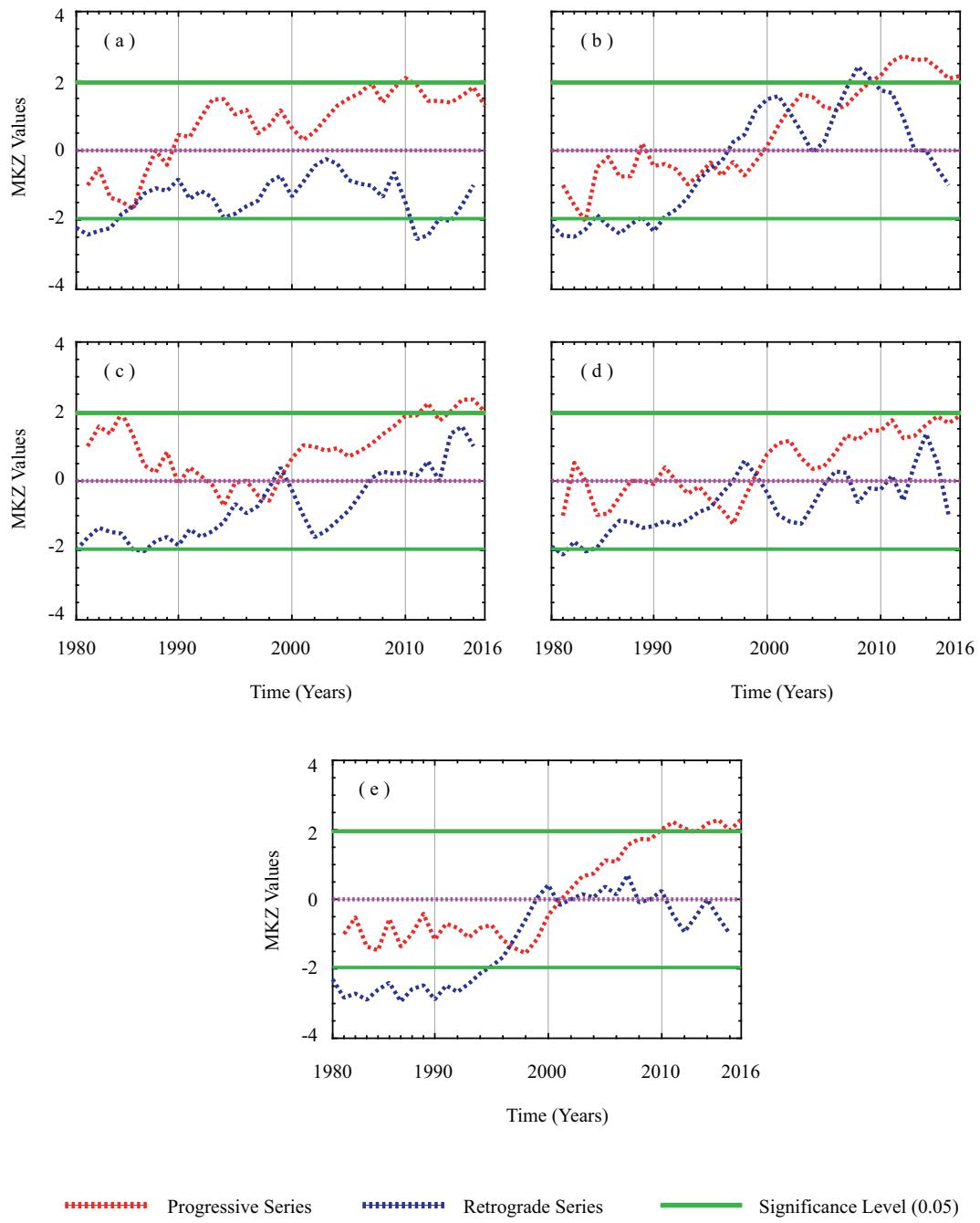


Fig. 9. Similar to Fig. 8, but for Tmin.

reported pronounced a warming trend with spatial variability in high altitudes than plain areas (Revadekar et al., 2013; Xu et al., 2018). The present study also noticed an increasing trend in the northern mountainous region, which affirm the findings of previous studies (Dharmaveer et al., 2015; Ren et al., 2017). According to Abbas (2013), many cities of Pakistan have been expanded in terms of population and urbanization, which may affect the long-term temperature of the country. Furthermore, various agricultural practices such as increased irrigation and different cropping patterns may have potential impacts on long-term temperature trends in the Indian sub-continent (Roy et al., 2016). As Pakistan is an agricultural based country and a major proportion of the country's land is used for agricultural purposes. Therefore, the agricultural practices adopted by local farmers can play a significant role in increasing trend of long-term temperature in the study region.

The decreasing trend of seasonal and annual Tmax and Tmin in some stations may be the result of topography, orographic factors, cloud cover, proximity to the river, precipitation amount and thereby different thermodynamic processes in the study region (Rahman and Dawood, 2017). Most of these stations with decreasing trend are located in the Piedmont of hills, which can influence the local temperature (Abbas, 2013). Moreover, the stations with a decreasing trend of Tmax and Tmin are mostly located in monsoon and westerlies core regions. Therefore, high cloud cover with complex topography during monsoon and westerlies seasons could result in decreasing trend of Tmax (Álvarez-Rodríguez et al., 2017; Revadekar et al., 2013). Moreover, the western disturbance and monsoon weather systems may also be responsible for variations in long-term trends of Tmax in the study area (Dimri et al., 2015; Priya et al., 2015; Shi et al., 2018a, 2018b). In recent studies, a negative correlation of temperature and precipitation

has been reported in monsoon and westerlies dominated regions of Pakistan and neighboring country, India (Iqbal et al., 2016; Subash and Sikka, 2014). The emission of greenhouse gases (GHGs) plays a vital role in increasing of long-term temperature and warming of a region (You et al., 2017). However, over the last two decades, a large number of industries, factories, and manufacturing units have been shut down in these cities, which may reduce utilization of fossil fuels and ultimately the emission of GHGs. According to Qasim et al. (2016), most of the cities are mountainous towns or in the vicinity of mountains having less environmental pollution, which could be one of the factors of the decreasing trend of Tmin.

In recent decades, the spatiotemporal variations of Tmax and Tmin have brought considerable changes in the natural and built environment of Pakistan. Overall, the country has experienced a consistent pattern of warming in Tmax and Tmin during the study period. The results are consistent with the findings of previous studies conducted at local, regional and global levels (Barry et al., 2018; Donat et al., 2014; Grotjahn et al., 2016; Klein Tank and Könen, 2003; Rao et al., 2014; Revadekar et al., 2013; Sun et al., 2017; Xu et al., 2018). The positive of trends of Tmax and Tmin at seasonal and annual scales may have potential implications on agriculture in Pakistan. The increasing trend of Tmax and Tmin would have positive impacts on agriculture by reducing the growing season and enabling the farmers' community to grow two or more crops per year (Mahmood and Jia, 2016). In recent years, the concept of multiple cropping system has gained significant attention and the local farmers are growing more than two crops per season due to shortening of the crop season (Arshad et al., 2017; Ullah et al., 2017). On the other hand, the rise in Tmax and Tmin may have a significant effect on the evapotranspiration, and certainly on agriculture sector of the country (Sultana et al., 2009). According to Abbas (2013), the rise in long-term temperature can increase the intensity of solar radiation and humidity which ultimately leads to high evapotranspiration. Due to high evapotranspiration, the crops require more water, which may affect the soil moisture system (Berardy and Chester, 2017). Similarly, the rapid increase in local Tmax and Tmin coupling with sunshine and relative humidity may affect several food crops including wheat, fruits and vegetables (Ali et al., 2017). Thus, the persistence increase of Tmax and Tmin will pose potential risks to sustainable crop production and agriculture sector.

In addition, the spatial and temporal variations of Tmax and Tmin may affect the hydrology of the country. These changes have resulted in several temperature extremes, including floods, drought and heat waves in the study region. Floods (2010), drought (1997–2002) and heat waves (2015) are the witnessed of these temperature extremes in recent decades (Islam et al., 2009; Rahman and Khan, 2011; Rohini et al., 2016; Zahid and Rasul, 2012). The rapid warming in northern Pakistan can exacerbate the process of glaciers and snow melting, which provide a large proportion of water for drinking, irrigation and other domestic purposes in downstream regions (Ahmad et al., 2015; Mahmood and Jia, 2016). However, excessive melting of snow and glaciers can overflow the rivers and may result in catastrophic flooding in the low-lying areas (Gadiwala and Burke, 2013; Xie et al., 2013). Similarly, the increasing trend of Tmax and Tmin in the central and southern regions of the country may have potential consequences in terms of drought and heatwaves. Several studies have projected that major parts of the country are highly vulnerable to hydro-meteorological disasters in future (Asmat et al., 2017; Asmat and Athar, 2017; Islam et al., 2009; Nasim et al., 2018). Thus, all these findings can be used as a base for tackling climate change problem and devising a long-term plan for adaptation of future climate change in the study area.

6. Conclusion

The current study assessed observed changes in seasonal and annual Tmax and Tmin over CPEC during 1980–2016. The long-term temporal analysis indicates that both Tmax and Tmin were significantly

increased on seasonal and annual scales; however, the trends of seasonal and annual Tmin were greater than Tmax. The spatial analysis of Tmax indicates that the warming trend in seasonal and annual temperatures was obvious over the whole country; however, the northern and southwestern mountainous regions exhibited a sharp increasing trend during the study period. Similarly, the spatial distribution of Tmin also showed a pronounced warming trend in seasonal and annual temperatures over the entire country with a sharp increase in the southern, southwestern and southeastern parts of the country. According to the mutation (SQMK) test, most of the abrupt changes in seasonal and annual Tmax and Tmin time series have occurred during 1995–2010; however, the winter season of Tmax and Tmin showed abrupt negative changes in the early 1980s. In Tmax, sharp positive changes were detected during the period of 1997–2002, while in Tmin trends, the majority of the rapid changes was noticed during 1995–2009. Based on the present findings, the present study recommends that forthcoming studies should focus on the factors responsible for the spatiotemporal variability of Tmax and Tmin in the target region.

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